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EXPERIMENTAL SIMULATION OF DEGRADING STRUCTURES THROUGH ACTIVE CONTROL

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SUMMARY

In experimental studies of structural behaviour, it is often desirable, even necessary, to perform tests on a test structure from its undamaged state, through its damaged states, and finally to failure. The fact that experiments of this type are not often done primarily because of its prohibitive cost. In this paper, a testing procedure is proposed in which a test structure is allowed to undergo its degradation in real time yet it is not physically damaged, thus allowing it to be reused. The underlying concept is that of active structural control. Considerable research and development of active structural control in civil engineering has taken place relative to responsive control of structures against damaging environmental loads. While the use of active control systems to simulate damage in an experimental setting as proposed in this paper appears to be new, much of the existing knowledge base in active structural control is directly applicable. © 1998 John Wiley & Sons, Ltd.

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KEY WORDS: active structural control; test structure; experimental simulation

1. INTRODUCTION

Experimental studies through testing of reduced-scale and full-scale structural models in the laboratory or in the field have always played a key role in structural research and in validating analytical methods developed for, for example, seismic resistant design, damage assessment, and structural retrofit strategies. Recent experiences with damaging earthquakes, wind, and other environmental forces further suggest that greater emphasis will be placed on structural testing and experimental verification for years to come.

To exploit experimental testing and verification to their fullest, it is often desirable to perform tests on a structural model through its entire behaviour range, starting from its undamaged state, through its various damage states, and finally to its failure state. However, this type of experiments is not often performed primarily because of its prohibitive cost. Even if cost is not a limiting factor, tests of this type are not repeatable unless two or more identical structural models are fabricated. Furthermore, the damage process is not easily controlled, leading to difficulties in structural performance assessment throughout its damage process or degradation. Indeed, premature failure of a test structure often leads to premature termination of an experimental research program.

In view of the above, it is thus desirable to devise means whereby a test structure is allowed to undergo its degradation in real time and yet it is not physically damaged, thus allowing it to be reused. One of the

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methods that can be used to accomplish this goal is through active structural control as proposed in this paper. It represents application of the active control concept to structural engineering in an entirely different context.

2. BEHAVIOUR OF DEGRADING STRUCTURE

For the purpose of modeling and analysis, an undamaged n-degree-of-freedom structural system behaves linearly and can be adequately modelled by a system of linear ordinary differential equations in the form

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) = \mathbf{f}(t) \tag{1}$$

where $\mathbf{x} = [x_1, x_2, \ldots, x_n]^{\mathrm{T}}$ is the n-dimensional displacement vector, $\mathbf{f}$(t) represents the externally applied forces, and $\mathbf{M}$, $\mathbf{C}$, and $\mathbf{K}$ are, respectively $n \times n$ mass, damping and stiffness matrices.

As the structure degrades, its behaviour at any time t can be modelled as

$$\mathbf{M}\ddot{\mathbf{x}}(t) + \mathbf{C}\dot{\mathbf{x}}(t) + \mathbf{K}\mathbf{x}(t) + \boldsymbol{\Gamma}[\mathbf{x}(t)] = \mathbf{f}(t) \tag{2}$$

In the above, the last term on the left-hand side represents damage state of the structure at time t; the symbol $\boldsymbol{\Gamma}$, in its most general form, represents a generic integrodifferential operator.

The term $\boldsymbol{\Gamma}[\mathbf{x}(t)]$ in equation (2) in various forms has been widely used to model the degrading behaviour of a structure, ranging from

$$\boldsymbol{\Gamma}[\mathbf{x}(t)] = \mathbf{K}_1(t)\,\mathbf{x}(t) \tag{3}$$

representing a simple stiffness degradation process, to a wide variety of hysteretic behaviour representations. Examples in this class include bilinear and trilinear models[1–3] as well as the Bouc–Wen hysteretic models.[4, 5] Figure 1 shows a well-known bilinear damage model showing dependence of the restoring force, representing $\mathbf{K}\mathbf{x}(t) + \boldsymbol{\Gamma}[\mathbf{x}(t)]$ in equation (2) in the scalar case, on x.

In the case of a Bouc–Wen hysteretic damage model, the restoring force $r(t)$, representing again $\mathbf{K}\mathbf{x}(t) + \boldsymbol{\Gamma}[\mathbf{x}(t)]$ in equation (2) in the scalar case, can be of the form

$$r(t) = \alpha k x(t) + (1 - \alpha)\, k \delta z(t) \tag{4}$$

in which k is elastic stiffness, α is the ratio of post-yield to pre-yield stiffness, δ is yield deformation, and z is a non-dimensional hysteretic variable with $|z| \leqslant 1$ and

$$\dot{z} = \frac{1}{\delta}\,[A\dot{x} - \beta\dot{x}|z|^n - \gamma|\dot{x}|z|z|^{n-1}] \tag{5}$$

By adjusting the parameters A, β, γ and n in the model, one can control the scale and general shape of the hysteretic loop.

To allow the damage represented by $\boldsymbol{\Gamma}[\mathbf{x}(t)]$ in equation (2) manifest itself in the test structure usually means the introduction of irreversible damage to the structure, a situation rendering the test structure largely unusable in future experiments. An alternative means of introducing damage to the test structure while preserving its integrity is to apply another external but manipulable force

$$\mathbf{u}(t) = -\boldsymbol{\Gamma}[\mathbf{x}(t)] \tag{6}$$

to the structure. Indeed, equation (1) with $\mathbf{u}(t)$ added to its right-hand side results in equation (2). The critical difference is that the physical structure remains linear and undamaged where it, together with $\mathbf{u}(t)$, mimics a degrading structure modelled by equation (2).

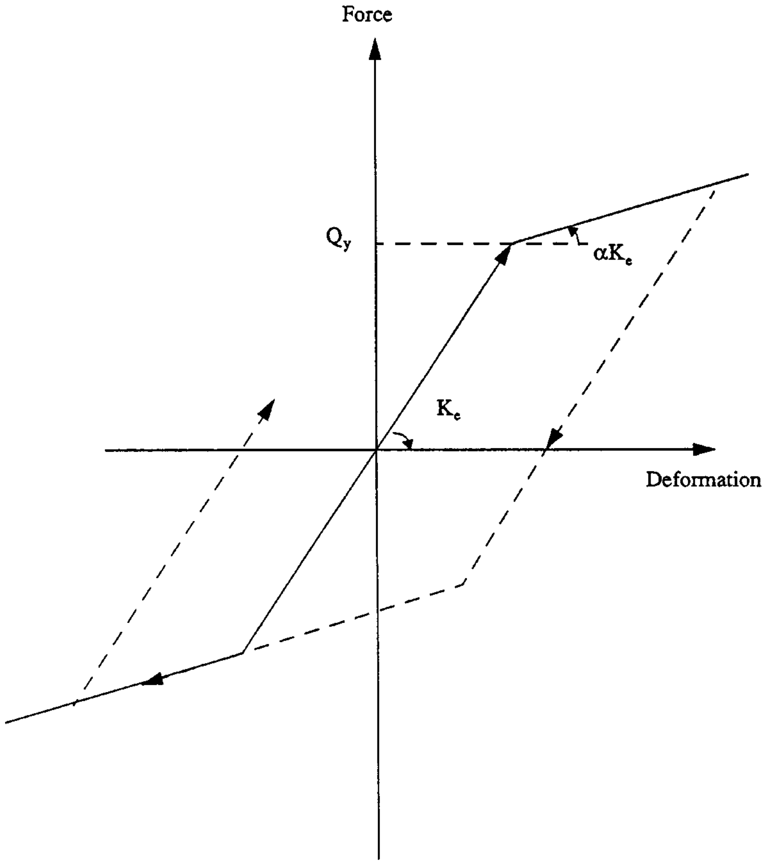


Figure 1. A bilinear damage model

3. REALIZATION OF $\mathbf{u}(t)$

The force $\mathbf{u}(t)$ defined in equation (6) shall be called the control force, which can be realized through feedback control schematically presented in Figure 2. The feedback loop consists of

(a) sensors located about the structure to measure appropriate response variables,
(b) controller to operate on the measured response in accordance with the form of $\mathbf{u}(t)$ defined in equation (6), and
(c) actuators to produce the control force $\mathbf{u}(t)$ and apply it to the structure.

It is clear that this feedback control scheme is identical to active control schemes for structural response reduction (Soong, 1990), but it is used in a different context. Damage models such as those given in equations (3) and (4) dictate the control law to be followed by the controller. The control law defined by equation (3), i.e.,

$$u(t) = -k_1(t)\,x(t) \tag{7}$$

in the scalar form, can be easily realized by storing $-k_1(t)$ at t_0, $t_0 + \Delta t$, $t_0 + 2\Delta t$, $\ldots$, where Δt is the sampling interval of the measured response, and multiplying at each sampling time by the measured response $x(t_0)$, $x(t_0 + \Delta t)$, $\ldots$.

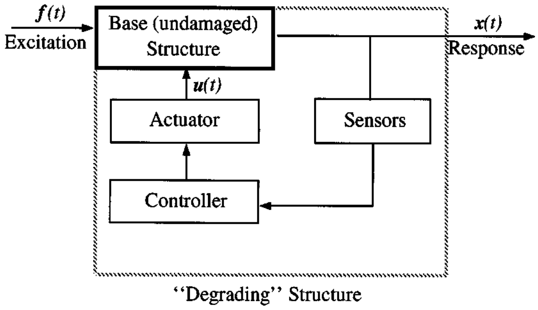


Figure 2. Block diagram of undamaged and degrading structures

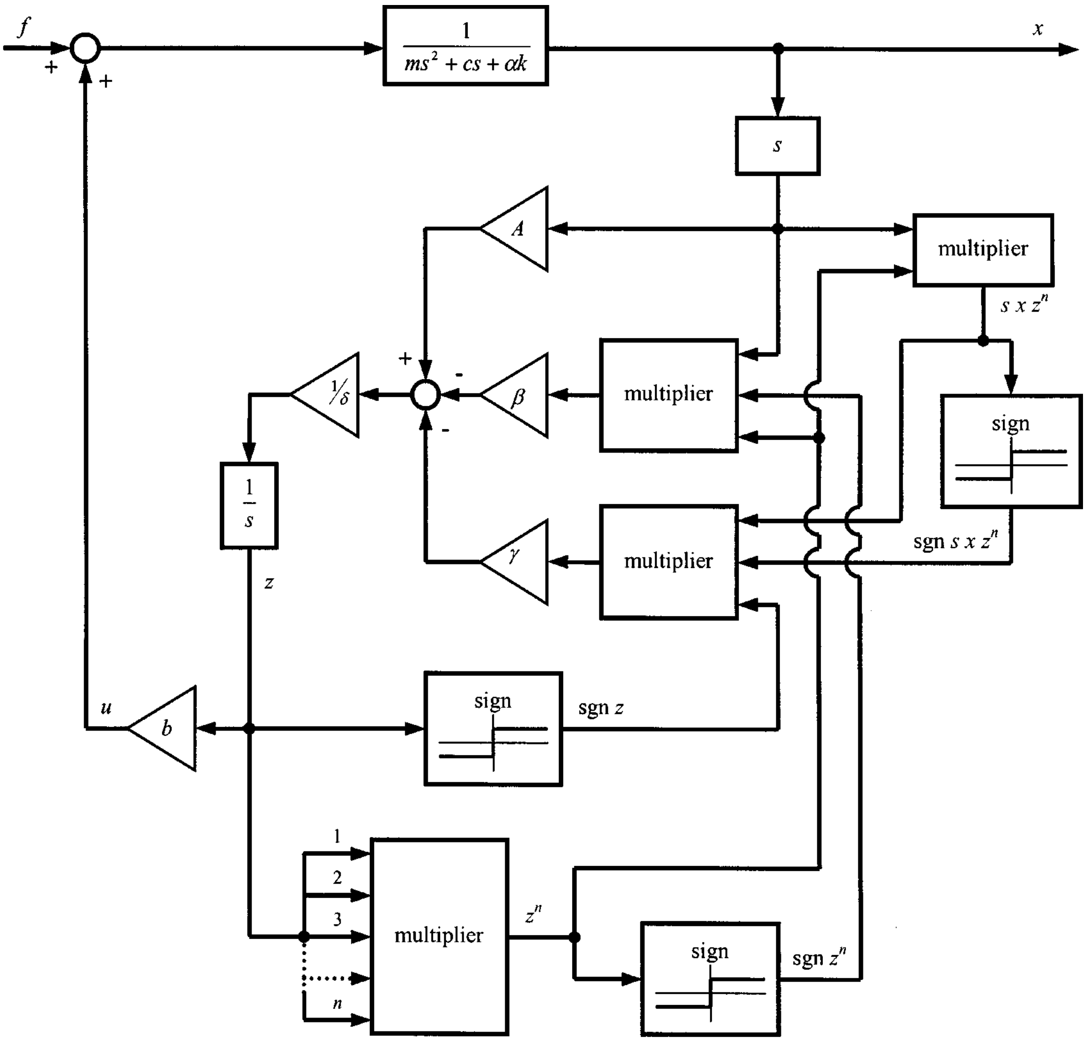


Figure 3. Block diagram of closed-loop system with Bouc–Wen hysteretic model

The realization of the control law governed by equations (4) and (5) is more complicated but can be accomplished through the construction of appropriate analog circuits.[6] In this case, the control force in the scalar case takes the form

$$u(t) = bz(t) \tag{8}$$

with $b = -(1-\alpha)k\delta$ and $z(t)$ satisfies equation (5). The block diagram of the closed-loop system representing the degrading structure is shown in Figure 3 with its accompanying analog circuit diagram sketched in Figure 4. It should be noted that while a scalar $u(t)$, being a function of the state variable $\mathbf{x}(t)$ as shown in

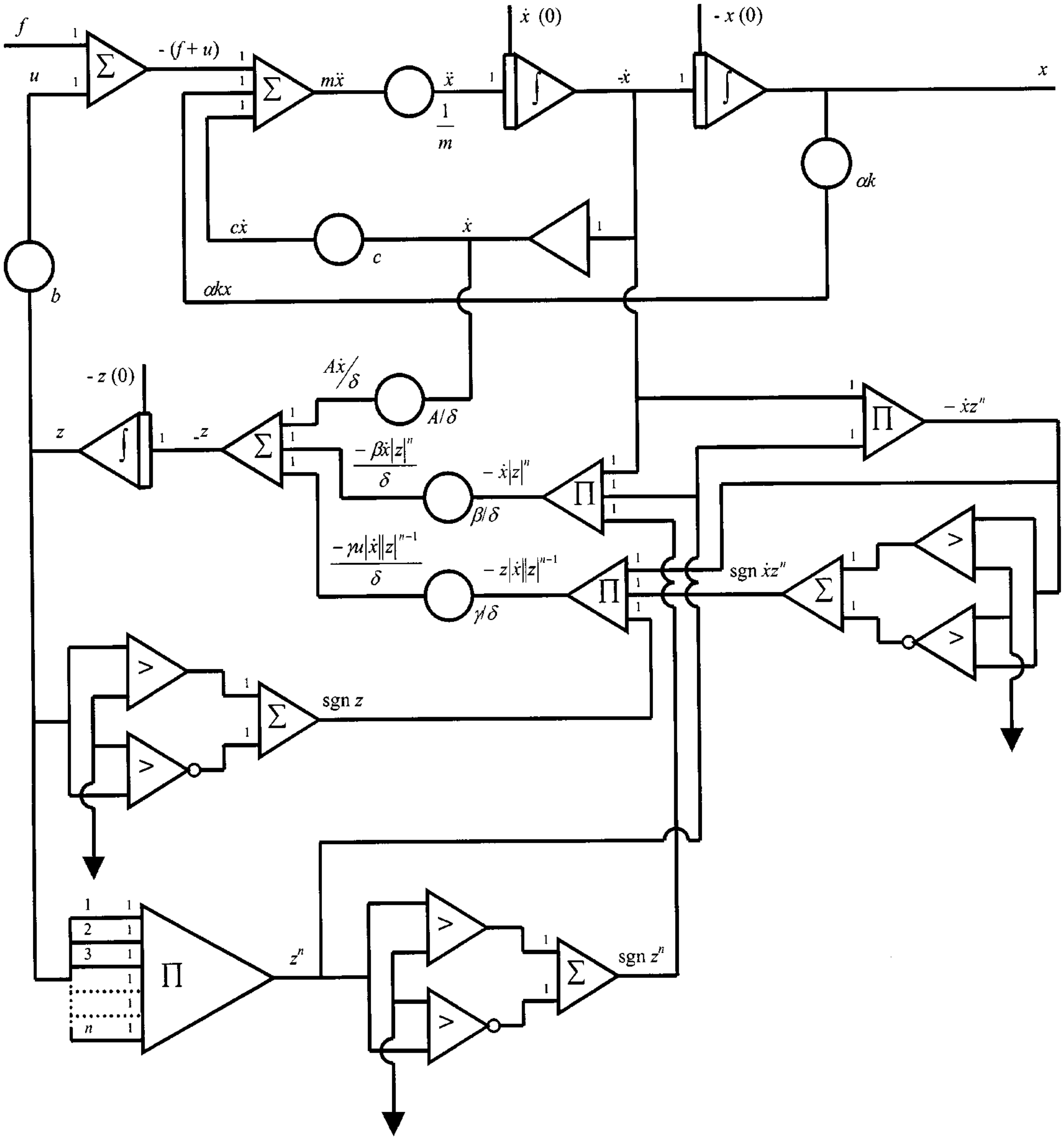


Figure 4. Analog circuit diagram of closed-loop system with Bouc–Wen hysteretic model

equation (6), is capable of generating multiple hysteretic elements, they are linearly dependent. Multiple control actuators are needed to generate multiple independent hysteretic elements.

It is seen that the degrading structure can be realized using the undamaged physical structure by incorporating the control loop into it. This representation is shown schematically in Figure 2.

4. ACTUATION MECHANISMS

Successful implementation of an active control system described in the preceding section presents many challenges, such as effect of time delay, modelling error effects, control/structure interaction, etc. Fortunately, many of these implementational related problems have been overcome to a large degree over the last 15 yr through extensive analytical and experimental research, and through full-scale system development. A successful experimental demonstration of this concept was made in the experimental verification of a damage assessment technique studied by Ge and Soong.[7]

While a number of control force delivery devices have been considered in active structural control,[8] two of which that have been successfully implemented in full-scale structures as well as in scaled test structures in the laboratory are active tendon or bracing systems and active mass damper systems[9–18] schematically presented in Figure 5. Either one of the systems can be used to experimentally simulate a degrading structure. The photographs of some of these systems are shown in Figures 6–9. Some of these, such as the active mass damper system shown in Figure 9(b), are stand-alone units and can serve as portable active control systems to generate "damage" to different test structures.

5. CONCLUDING REMARKS

This paper has outlined a procedure by which an experimental structure can undergo various damage states without being physically damaged through active control. Implementation of this procedure can be realized based on extensive research that has been carried out in active structural control, which has been orientated toward response control of structures against damaging environmental loads. In this application, active

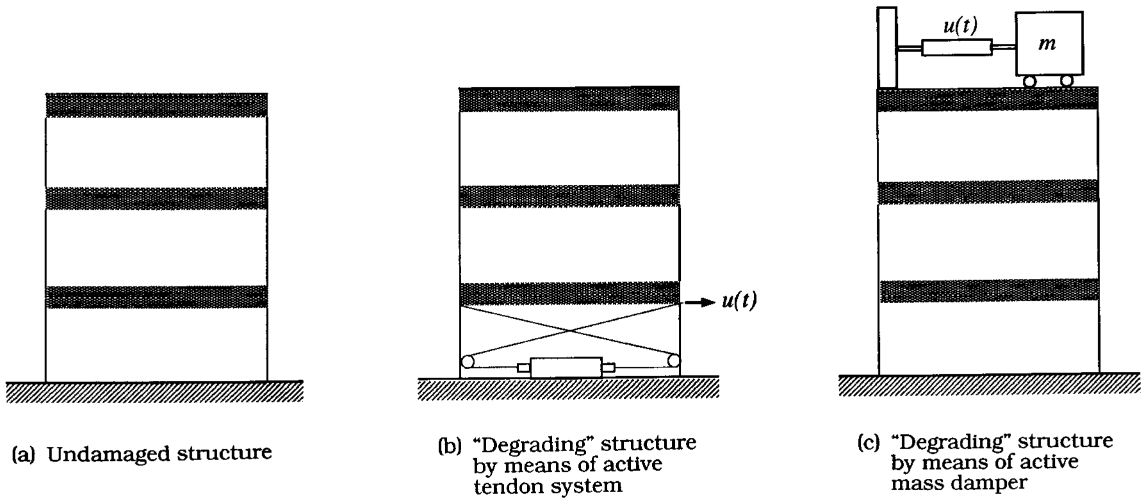
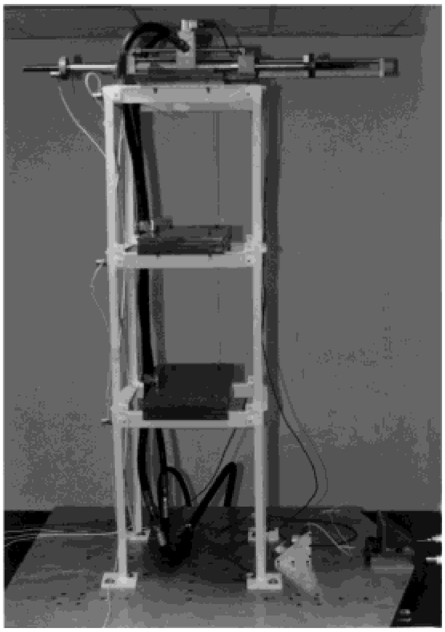
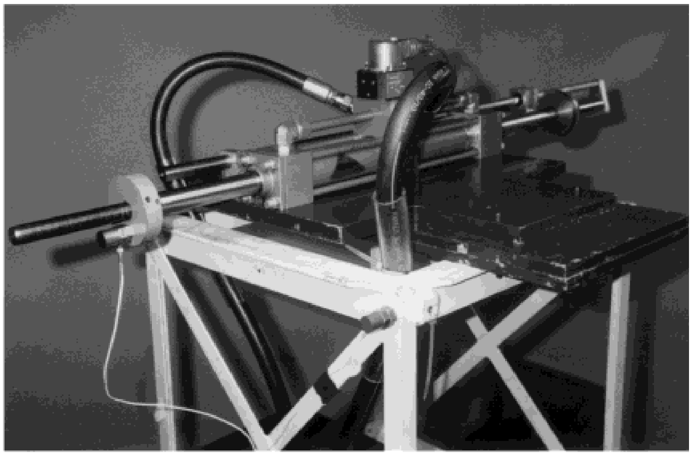


Figure 5. Experimental simulation of degrading structure

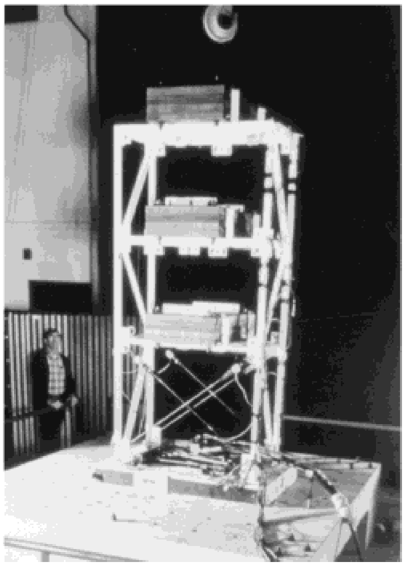


(a) Test structure
with active mass
damper on top floor

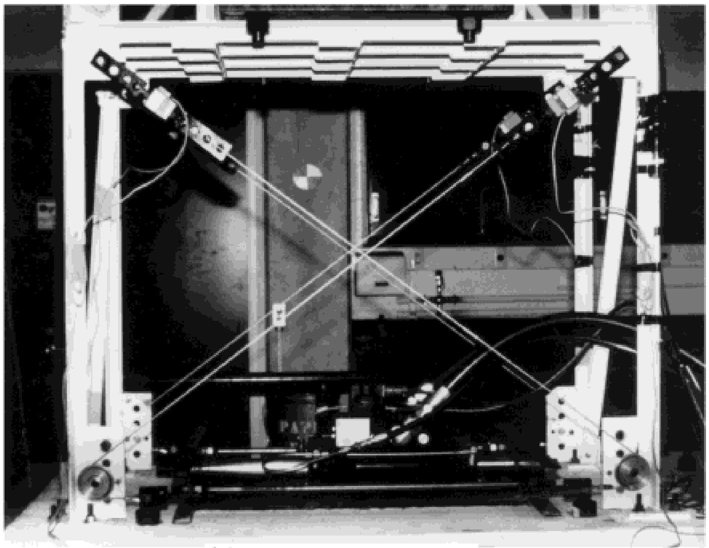


(b) Close-up view of
active mass damper

Figure 6. Active mass damper atop 500 lb three-storey test structure[11]

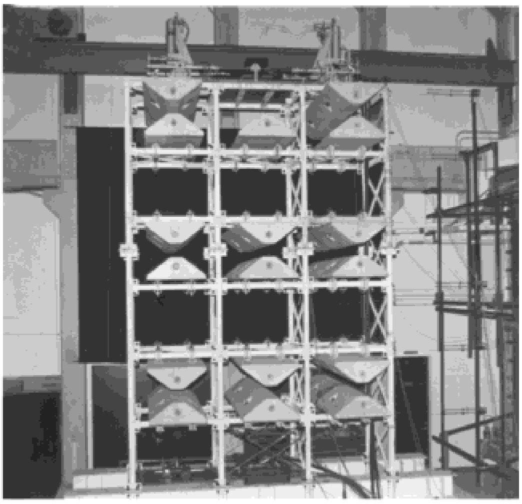


(a) Test structure with
active tendon system
attached to first floor

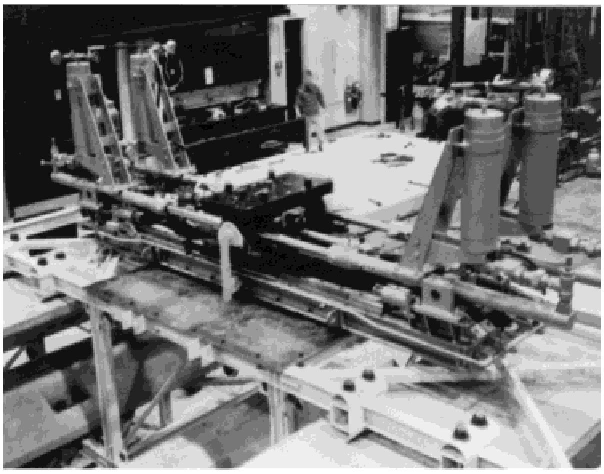


(b) Close-up view of
active tendon system

Figure 7. Active tendon system on ground floor of 6400 lb three-storey test structure[10]

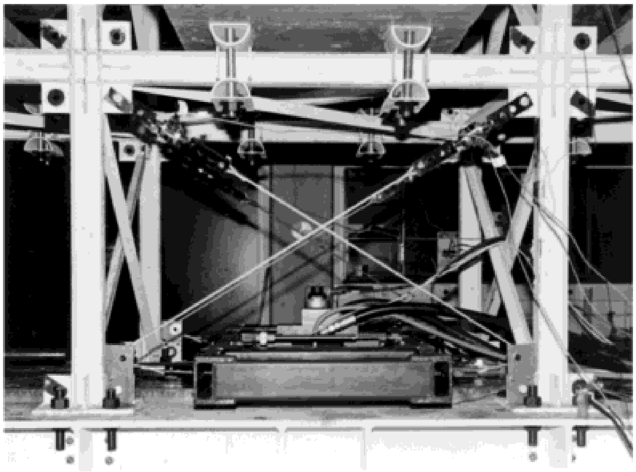


(a) Test structure with active mass damper on top and active tendon system attached to first floor



(b) Close-up view of active mass damper

Figure 8. 42,000 lb six-storey test structure with active mass damper on top and active tendon system on ground floor[16]

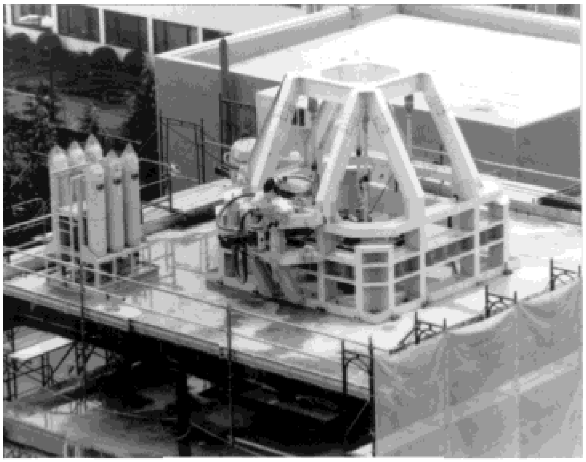


(c) Close-up view of active tendon system

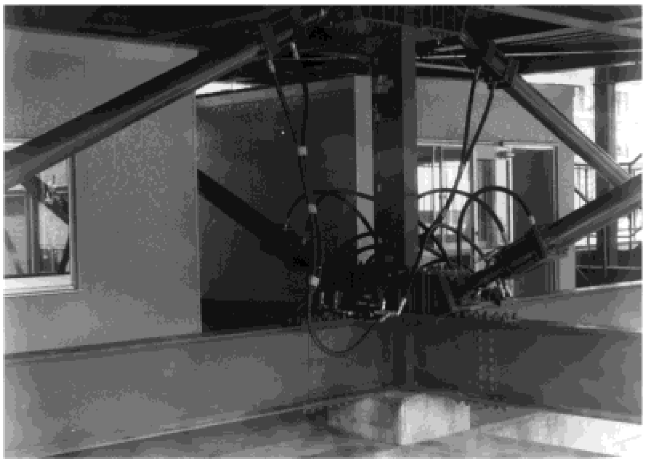
Figure 8. (*Continued*)

(a) Test structure with active mass damper on top (in enclosure) and active bracing system on ground floor

Figure 9. 600 ton full-scale six-storey test structure with active mass damper on top and active bracing system on ground floor[16,17]



(b) Close-up view of active mass damper



(c) Close-up view of active bracing system

Figure 9. (*Continued*)

control systems are used to generate damage instead of controlling damage, representing a new direction in the application of active control technology.

The most obvious advantage in using this procedure to simulate damage in test structures is that such test structures are allowed to undergo degradation and yet not physically damaged, thus allowing them to be reused. Other important advantages include the following:

(a) Experiments on test structures undergoing damage can be repeated.
(b) A variety of damage models can be simulated with the same control hardware by simply rewriting the control program. Thus, a test structure can be experimentally studied by varying severity and location of damage as well as the underlying damage process.
(c) The speed of degradation can be controlled, allowing more detailed studies as damages develop and evolve over time.

(d) It is entirely feasible to fabricate portable active control systems which can be applied to different test structures. This feature is attractive when several test structures are available in a testing laboratory or in the field.

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